

Bi₂Sr₂CaCu₂O_{8+δ} Bicrystal *c*-Axis Twist Josephson Junctions: A New Phase-Sensitive Test of Order Parameter Symmetry

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Li *et al.* [Phys. Rev. Lett. **83**, 4160 (1999)] prepared atomically clean Bi₂Sr₂CaCu₂O_{8+δ} (BSCCO) Josephson junctions between identical single crystal cleaves stacked and twisted an angle ϕ_0 about the *c*-axis. For each bicrystal, the ratio J_c^J/J_c^S of the *c* axis twist junction critical current density to that across either single crystal part is unity, independent of ϕ_0 and the ratio A^J/A^S of junction areas. From extensive theoretical studies involving a variety of tunneling and superconducting order parameter (OP) forms, we conclude that the results provide strong evidence for incoherent *c*-axis tunneling and that the dominant OP is *s*-wave for $T \leq T_c$. Recently, Takano *et al.* [Phys. Rev. B **65**, 140513(R) (2002)] obtained results from BSCCO whisker twist junctions which also rule out a pure *d*-wave OP, but which are surprisingly suggestive of coherent *c*-axis tunneling from small Fermi surface hot spots.

I. INTRODUCTION

Phase-sensitive experiments to test the symmetry of the superconducting order parameter (OP) in the high transition temperature (T_c) superconductors were mostly made on YBa₂Cu₃O_{7-δ} (YBCO) [1], for which the OP can have mixed ($d_{x^2-y^2} + s$) symmetry. To reconcile the various results, Müller proposed that the surface might be mostly $d_{x^2-y^2}$ -wave, and the bulk mostly *s*-wave [2]. Especially in Bi₂Sr₂CaCu₂O_{8+δ} (BSCCO), the *c*-axis transport above T_c is incoherent, [3], and scanning tunneling microscope studies revealed that it is electronically disordered on the scale of the superconducting coherence length, ≈ 1.5 nm [4], both unfavorable features for bulk *d*-wave superconductivity. Both *c*-axis Pb/BSCCO Josephson junctions [5] and a new phase-sensitive experiment on BSCCO are consistent with those observations [6].

II. THE BICRYSTAL TWIST EXPERIMENT

Li *et al.* cleaved a single crystal of BSCCO, twisted the two cleaves an angle ϕ_0 about the *c*-axis and fused them together, forming junctions of remarkably superior quality [6]. High resolution transmission electron spectroscopy and other studies revealed that the junction cross-sections were atomically clean over more than 5 μ m [7], far superior to those used in tricrystal experiments [1]. They measured the *c*-axis critical current I_c^S and I_c^J across a single crystal and the twist junction near to T_c , respectively, and the respective areas A^S and A^J .

They found that the ratio of the critical current densities $J_c^J = I_c^J/A^J$ to $J_c^S = I_c^S/A^S$ at $0.9T_c$ was independent of ϕ_0 , as shown in Fig. 1 [6]. Here we argue that these data demonstrate that the bulk OP in BSCCO is *s*-wave for $T \leq T_c$, and the *c*-axis quasiparticle tunneling is strongly incoherent.

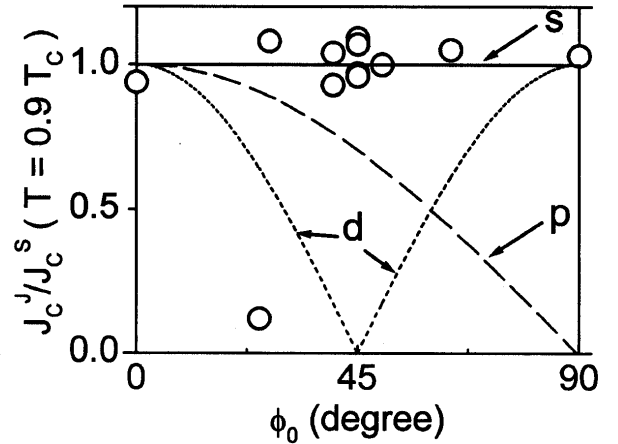


FIG. 1. Ratio at $0.9T_c$ of the critical current densities J_c^J/J_c^S across *c*-axis twist junctions to that across single crystals of BSCCO, versus the twist angle ϕ_0 . [6] The curves are theoretical results for strongly incoherent *c*-axis tunneling. [10]

III. GROUP THEORY AND THE FERMI SURFACE

Both YBCO and BSCCO are orthorhombic, but in different ways. For YBCO with point group C_{2v}^1 , the mirror planes σ_x, σ_y (the *ac, bc* planes) contain the crystal axes *a* and *b* along the Cu-O bond direction in the CuO₂ layers. In BSCCO with approximate point group C_{2v}^{13} , the mirror plane σ_b (the *bc*-plane) contains the *b* crystal axis (along a diagonal between the Cu-O bond directions) and the periodic lattice distortion [7,8]. The irreducible representations for the OPs in YBCO and BSCCO are given in Table I. Although *s*- and $d_{x^2-y^2}$ -wave OP components are compatible in the bulk of YBCO, they are *incompatible* in BSCCO, requiring a second phase transition for bulk coexistence.

We assume the quasiparticle dispersion has either the tight-binding $\xi(\mathbf{k}) = -t[\cos(k_x a) + \cos(k_y a)] + t' \cos(k_x a) \cos(k_y a) - \mu$ with $t = 306$ meV, $t'/t = 0.90$, and $\mu/t = -0.675$, or hot spot $[\cos(k_x a) - \cos(k_y a)]^2 - \nu^2$ forms, and a respective tetragonal Fermi surface (FS)

with $\xi(\mathbf{k}_F) = 0$, shown in Fig. 2 [9,10].

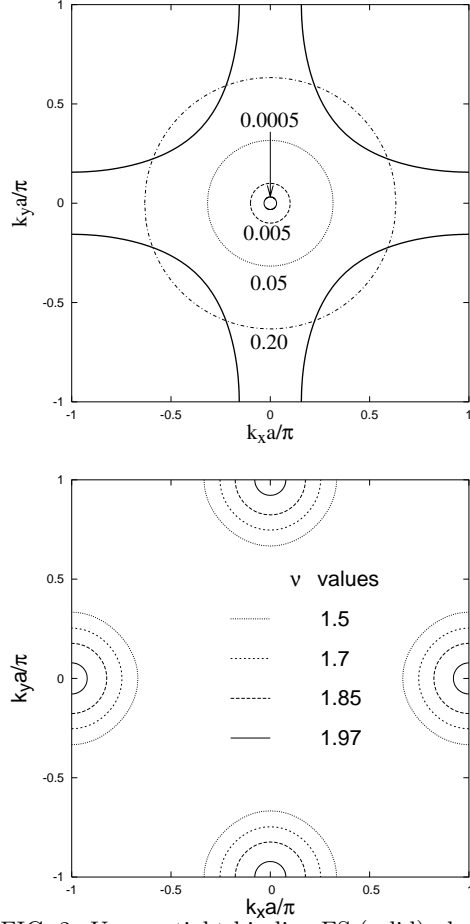


FIG. 2. Upper: tight-binding FS (solid) plus f^J half-width regions for indicated $\tilde{\sigma}^2$ values. [10] Lower: hot spot FSs with $\nu = 1.5, 1.7, 1.85, 1.97$.

IV. THE TWIST THEOREM AND ITS CONSEQUENCES

For weak tunneling across the twist junction,

$$J_c^J(\phi_0) = |4eT \sum_{\omega} \langle f_{\mathbf{k},\mathbf{k}'}^J F_{\omega,\mathbf{k}} [R_{\mathbf{k}'}(\phi_0) F_{\omega,\mathbf{k}'}] \rangle|, \quad (1)$$

TABLE I. Irreducible representations (IR) of the OPs for orthorhombic point groups C_{2v}^1 for YBCO (left) and C_{2v}^{13} for BSCCO (right).

IR	YBCO OP	σ_x, σ_y	IR	BSCCO OP	σ_b
A_1	$ s + d_{x^2-y^2}\rangle$	+1	A'_1	$ s + d_{xy}\rangle$	+1
A_2	$ d_{xy} + g_{xy}(x^2-y^2)\rangle$	-1	A'_2	$ d_{x^2-y^2} + g_{xy}(x^2-y^2)\rangle$	-1

where $F_{\omega,\mathbf{k}} = \Delta(\mathbf{k})/[\omega^2 + \xi^2(\mathbf{k}) + |\Delta(\mathbf{k})|^2]$, $\Delta(\mathbf{k})$ is the OP, ω represents the Matsubara frequencies, $f_{\mathbf{k},\mathbf{k}'}^J$ is the tunneling matrix element squared, $\langle \dots \rangle$ is an average over each first Brillouin zone (BZ), and $R_{\mathbf{k}'}(\phi_0)$ rotates the wave vectors \mathbf{k}' by ϕ_0 about the c -axis. For a single d -wave OP component, $R_{\mathbf{k}}(\pi/2)\Delta(\mathbf{k}) = -\Delta(\mathbf{k})$.

Twist Theorem 1 For any weak tunneling matrix element squared satisfying $f_{\mathbf{k},\mathbf{k}'}^J = f_{\mathbf{k}',\mathbf{k}}^J$, an arbitrary OP of general $d_{x^2-y^2}$ - or d_{xy} -wave symmetry in a tetragonal crystal gives rise to a vanishing c -axis critical current across an internal 45° twist junction for $T \leq T_c$.

PROOF

$$\begin{aligned} Z_\omega &= \langle f_{\mathbf{k},\mathbf{k}'}^J [R_{\mathbf{k}'}(\pi/4) F_{\omega,\mathbf{k}'}] F_{\omega,\mathbf{k}} \rangle \\ &= \langle f_{\mathbf{k},\mathbf{k}'}^J F_{\omega,\mathbf{k}'} [R_{\mathbf{k}}(-\pi/4) F_{\omega,\mathbf{k}}] \rangle \\ &= \langle f_{\mathbf{k},\mathbf{k}'}^J F_{\omega,\mathbf{k}'} [-R_{\mathbf{k}}(\pi/4) F_{\omega,\mathbf{k}}] \rangle \\ &= \langle f_{\mathbf{k}',\mathbf{k}}^J F_{\omega,\mathbf{k}} [-R_{\mathbf{k}'}(\pi/4) F_{\omega,\mathbf{k}'}] \rangle = -Z_\omega = 0. \end{aligned}$$

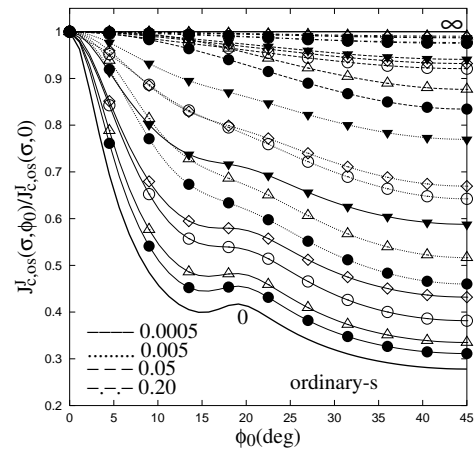
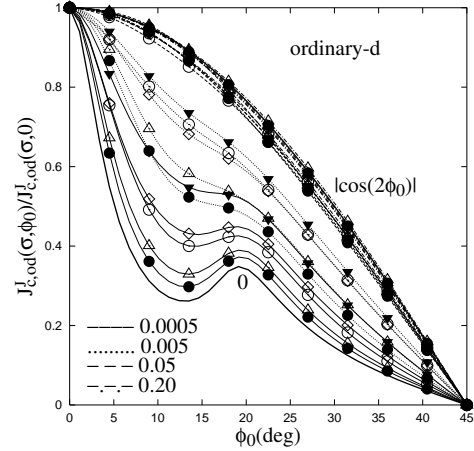


FIG. 3. Plots of $J_c^J(\phi_0)/J_c^J(0)$ near T_c with the tight-binding FS in Fig. 2 for the ordinary $d_{x^2-y^2}$ (top) and s (bottom) OPs. The thick solid lines labelled 0 are for coherent tunneling, and those labelled $|\cos(2\phi_0)|$ and ∞ are for purely incoherent tunneling. Other curve types labelled with the values of $\tilde{\sigma}^2$ measure the fraction of the first BZ involved in the tunneling, as shown in Fig. 2. Results for the Gaussian (\bullet), exponential (\circ), Lorentzian (\diamond) rotationally-invariant Lorentzian (\triangle), and stretched Lorentzian (solid inverted triangles) f^J forms are shown. [10]

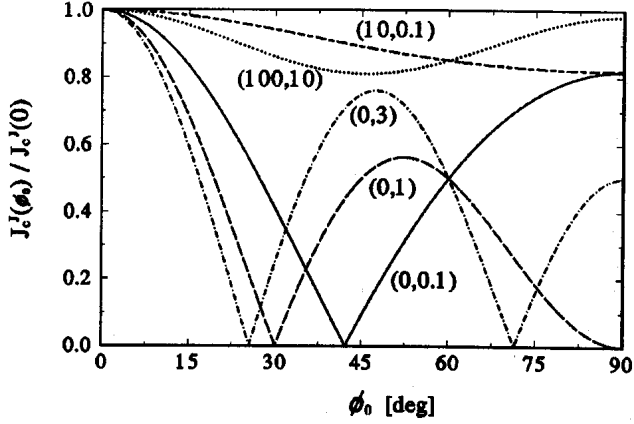


FIG. 4. Plots of $|A + \cos(2\phi_0) + B \cos(4\phi_0)|/|1 + A + B|$, with the A, B values, for $J_c^J(\phi_0)/J_c^J(0)$ from the A'_1, A'_2 OP IRs. [8]

We studied a variety of OP and weak $f_{\mathbf{k},\mathbf{k}'}^J$ forms [10]. In Fig. 3, we show our results for the ordinary- d - and ordinary- s - OP forms proportional to $\cos(k_x a) - \cos(k_y a)$ and 1, respectively. For a Gaussian form of f^J , $f_{\mathbf{k},\mathbf{k}'}^J = f_0^J \exp[-(\mathbf{k} - \mathbf{k}')^2/\tilde{\sigma}^2]$. We also studied exponential, Lorentzian, rotationally-invariant Lorentzian, and stretched Lorentzian forms [10]. Regardless of the form of f^J , the twist theorem requires $J_c^J(\pi/4) = 0$ for a d -wave OP. From these and similar unpictured curves, it is evident that only an OP of general s -wave symmetry can fit the data. Moreover, the c -axis quasiparticle tunneling must be very incoherent.

A. Orthorhombicity

When orthorhombicity is included, the theorem is not rigorous. However, including a small $g_{xy(x^2-y^2)}$ OP component in a dominant- $d_{x^2-y^2}$ A'_2 OP will only shift the angle ϕ_0^* at which $J_c^J(\phi_0^*) = 0$ by a small amount from 45° , as pictured in Fig. 4. Hence, orthorhombicity cannot explain the data of Li *et al.* [6].

B. Order Parameter Twisting

At low T , it is possible to obtain $J_c^J(\pi/4) \neq 0$ with a predominant- $d_{x^2-y^2}$ A'_2 OP symmetry, provided that a subdominant A'_1 OP component can exist. Near to the twist junction, the dominant A'_2 OP would be suppressed, and the subdominant A'_1 OP increases in amplitude, so that the overall OP effectively rotates near the twist junction [8]. However, the amount of twisting is strongly limited by the second bare transition temperature T_{cB}^0 and by the bulk and twist junction Josephson coupling strengths η, η' . In Fig. 5, we show the results obtained with subdominant OPs of the d_{xy} - and s -wave forms, respectively. Neither case can fit the data of Li *et al.* [6]. Figure 5 shows that an experiment just below T_c can rule out OP twisting effects, unless $T_{cB}^0 = T_c$, for which the overall bulk OP would be nearly isotropic at low T .

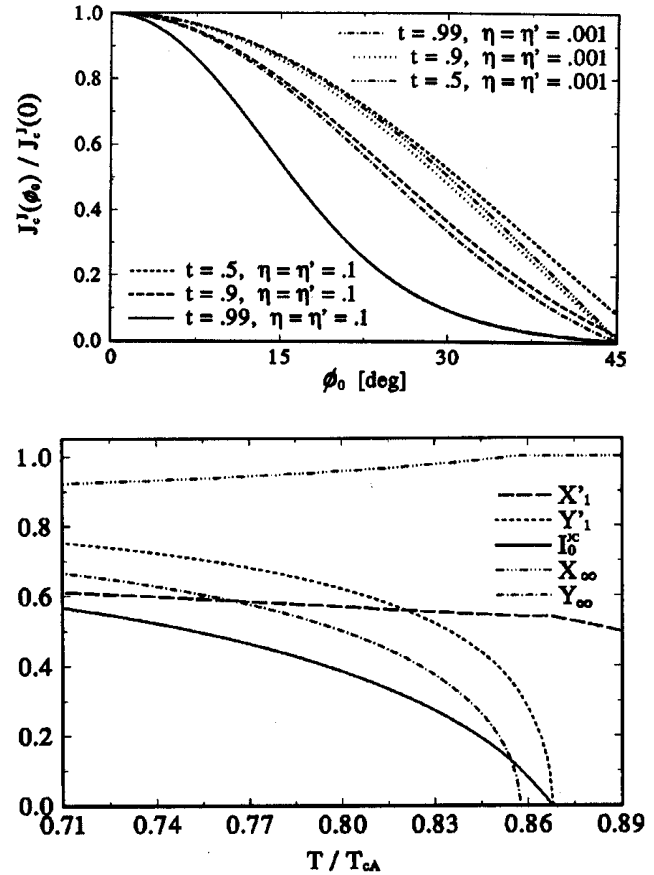


FIG. 5. Upper: Plots of $J_c^J(\phi_0)/J_c^J(0)$ at different $t = T/T_c$ values for a $d_{x^2-y^2} + id_{xy}$ symmetry in the bulk, with $T_{cB}^0 = 0.1T_c$. η and η' are the Josephson couplings across bulk and the twist junctions, respectively. Lower (solid): $T/T_{cA} = t$ dependence of $J_c^J(45^\circ)$ for a twist junction with $d_{x^2-y^2} + is$ symmetry in the bulk, and $T_{cB}^0 = 0.9T_c$. [8]

C. Strong Coupling and Other Models

We also considered both weak and strong coherent c -axis tunneling with a variety of FS forms [9]. In Fig. 6, we show the tight-binding FS $J_c^J(\phi_0)$ for second order coherent tunneling. In Fig. 7, the $J_c^J(\phi_0)$ for weak coherent tunneling with two hot spot FSs in Fig. 2 are shown. None of these curves fit the data of Li *et al.* [6].

V. BSCCO WHISKER C -AXIS TWIST EXPERIMENTS

Recently, Takano *et al.* performed low- T c -axis twist mesa experiments using overdoped BSCCO whiskers with $45^\circ \leq \alpha \equiv \phi_0 \leq 90^\circ$ [11]. Their data, pictured in Fig. 7, are distinctly different from those of Li *et al.* [6], with a strong $J_c^J(\phi_0)$ dependence. Especially since $J_c^J(\phi_0)$ for $\phi > 80^\circ$ was anomalously large, Takano *et al.* suspected an extrinsic ϕ_0 dependence to $f_{\mathbf{k},\mathbf{k}'}$ [11]. Nevertheless, in Fig. 7 we fit the data using Eq. (1) by assuming the quasiparticles have a hot spot dispersion and intrinsically coherent c -axis tunneling. Subsequently, they found $J_c^J(\phi_0) \approx C \neq 0$ from many junctions with $\phi_0 \approx 45^\circ$, and provided preliminary Fraunhofer and Shapiro evidence that the non-vanishing $J_c^J(45^\circ)$ arises from first-order Josephson tunneling [12]. Hence, the whisker experiments rule out a pure A'_2 (e. g., $d_{x^2-y^2}$) OP, but are presently consistent with an OP either of pure A'_1 (e. g., s) symmetry, or of mixed A'_1 and A'_2 (e. g., $d_{x^2-y^2} + is$) symmetry. From our theoretical studies, whisker experiments just below T_c might determine if their bulk OP is also pure A'_1 [6], and measurements above T_c could investigate if the c -axis transport is indeed coherent, strikingly inconsistent with single crystal BSCCO [3].

VI. CONCLUSIONS

The data of Li *et al.* demonstrate that the OP in the bulk of BSCCO has A'_1 (s) symmetry for $T \leq T_c$, and that the c -axis tunneling is strongly incoherent. The data of Takano *et al.* presently rule out a pure A'_2 ($d_{x^2-y^2}$) OP, but surprisingly suggest that the weak c -axis tunneling in BSCCO whiskers might be coherent with a FS consisting of small hot spots.

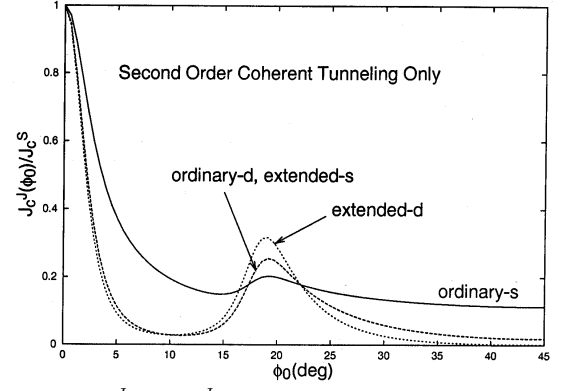


FIG. 6. $J_c^J(\phi_0)/J_c^J(0)$ near to T_c for the s , $d_{x^2-y^2}$, extended- s [$|\cos(k_x a) - \cos(k_y a)|$] and extended- d OPs, [10] obtained for coherent second order twist junction tunneling only.

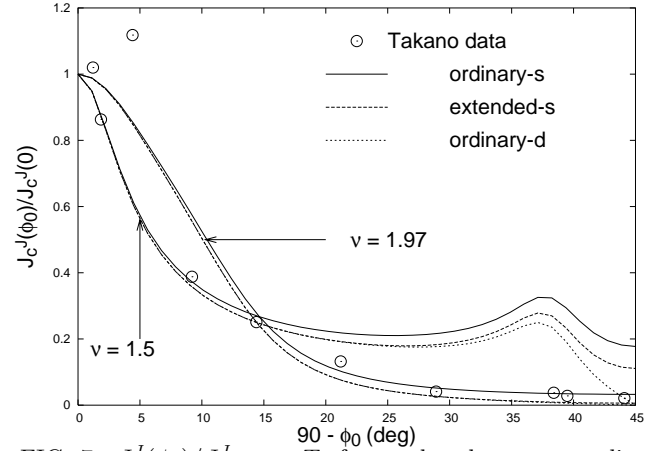


FIG. 7. $J_c^J(\phi_0)/J_c^J(0)$ near T_c for weak coherent tunneling with the hot spot FSs in Fig. 2 with $\nu = 1.5, 1.97$, for the ordinary- s , extended- s , and ordinary- $d_{x^2-y^2}$ OPs. The whisker data (\circ) of Takano *et al.* are also shown. [11]

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